SPEED CONTROL OF SVPWM INVERTER FED BLDC MOTOR DRIVE

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Technology

in

Electrical Engineering
(Specialization Industrial Electronics)

by

Sumit Mandal

Department of Electrical Engineering

National Institute of Technology

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Under the Guidance of

Dr. Susovon Samanta

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CERTIFICATE

This is to certify that the thesis entitled, "Speed Control of SVPWM Inverter fed BLDC Motor Drive" submitted by Sumit Mandal in partial fulfilment of the requirements for the award of MASTER of Technology Degree in Electrical Engineering with specialization in "Industrial Electronics" at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any degree or diploma.

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Sumit Mandal
212EE5262

ABSTRACT

Brushless DC motors have a very wide area of applications due to their higher efficiency and easy control strategies. For controlling the BLDC motors we use three phase bridge converters. In BLDC motors only two phases are supplied and the third phase is kept off. Which two phases are to be supplied is determined on the basis of the position of the rotor. Based on the position of the rotor, switching devices in the inverter are commutated for every 60 degree. Rotor position sensors are used to sense the position of the rotor at every instant of time. For controlling the output voltage and frequency of the inverter Pulse Width Modulation (PWM) techniques are used. Sinusoidal PWM and Space Vector PWM (SVPWM) are the most used techniques today. Sinusoidal PWM is the simplest and most used PWM techniques today, but it has many flaws. The newly invented Space Vector PWM technique reduces these flaws such as it reduce switching loses, harmonic content in the output, better utilization of available dc-bus voltages. This thesis presents PI controller for the speed control of BLDC motor fed by a SVPWM inverter. The PI controller leads to improve the behaviour of the motor. The use of SVPWM inverter reduces the size of the battery or power source. The SVPWM technique for inverter and speed control for BLDC motor is simulated using Matlab software package.

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List of Symbols:

R_s- Stator resistance per phase	
L	- Stator inductance per phase
M	-Mutual inductance between phases
ω_m	-Angular speed of the motor
θ	-Angular position of rotor
λ_m	-Flux Linkages
J	- Moment of inertia
B	-Damping constant
T_e	-Electromagnetic torque
T_l	-Load torque
K_p	-Proportional constant
K_i	-Integral constant
e(t)	-Speed error

Chapter 1:

INTRODUCTION

1.1 Introduction

Brushless DC motors (BLDC) are variable frequency permanent magnet synchronous motors having very similar torque speed characteristics to that of DC motors that's why the name Brushless DC came. It requires an electronic circuit for commutation instead of brushes. Today the uses of BLDC motor have increases and its competing with induction motor and DC motors. BLDC motor need an inverter to fed power. Inverters are used to convert ac power into dc power we can control the output voltage and output frequency of the inverter as per our requirement. The output waveform of the inverter depends on the switching state of the inverter. Studied are carried out for meeting the requirement of inverters such as reduce harmonic content in the output, switching frequency of the inverter and better consumption of the available dc voltage. One of the most common methods used for inverter switching is Pulse width modulation (PWM) Techniques. In this technique we control the output voltage by varying the on-off time of the switching elements in the inverter. The most popular PWM techniques used today are Sinusoidal PWM (SPWM) and Space Vector PWM (SVPWM). With the increase in use of microcontroller SVPWM become most important PWM methods for inverters. In SVPWM we compute the on-off time for each switch.

1.2 Motivation

Since the ends of the 19th century Brushed DC motors are used for different applications and it's become the most used motor for commercial operations. With the development of brushless DC motors its gives competition to the use of Brushed DC motor. BLDC motor was supplied by three-phase inverter. PWM technique is used to achieve desired voltage and frequency from the inverter. Different PWM techniques are used to control the inverter output, the SPWM is most commonly used techniques. In mid-80’s SVPWM technique is derived and its use also increases. SVPWM is easy to implement using microcontrollers and also reduce harmonics in the output, reduce switching frequency of the inerter and utilizes dc link voltage better.

1.3 Literature Review

Pulse width modulation (PWM) schemes are increasingly used today in inverter control for ac drives. PWM techniques are used to control both magnitude and frequency of the voltage applied to motor [1]. Various PWM techniques, control techniques for inverter, and implementation of these techniques are studied [10]. PWM techniques are used to reduce the harmonic content and switching losses, the main objective of PWM is to minimize harmonics and obtain maximum power [6].Different topologies for BLDC motor with inverter has been studied [14].BLDC motor dynamics are very similar to that of a DC motor the Dynamic model and state space model is studied [7, 8]. The implementation of SVPWM with the BLDC motor and the controller design for controlling the speed of BLDC motor has been studied [12, 13].

1.4 Review on brushless dc motor

With the on-going research on permanent magnet motors, like brushless dc motor (BLDC) shows many advantages over the induction motor. The BLDC motor has trapezoidal back-emf characteristics and requires constant stator current at the middle to phase voltage waveform to produce a constant torque. The torque speed characteristics of BLDC motor is similar to that of a dc motor. Permanent magnet synchronous motor (PMSM) exhibits sinusoidal back-emf and to produce constant torque it’s required a sinusoidal shaped current. PMSM is similar to the synchronous machine with a permanent magnet rotor instead of field winding. Therefore the d-q axis modelling of the PMSM can be obtained. On the other hand in BLDC motor the back- emf is trapezoidal so the transformation in d-q axis is not suitable as it cannot map the inductance of the a-b-c frame into d-q frame. Hence a-b-c model of BLDC motor is used instead of d-q model.

1.5 Review on BLDC motor control

The control principle for the trapezoidal BLDC motors is that only two stator winding should carry current at an instant of time and the third winding should been kept off. No torque should be producing during back-emf zero crossing for each individual stator phase. Trapezoidal BLDC motors are often equipped with transducers to detect the back EMF zero-crossing regions. The inverter gate switching logic can be obtained through a truth table based on the status of a set of Hall-effect sensor outputs. Theoretically, constant torque can be generated with the rotor position feedback, as the back EMF is constant when the phases are switched on. However, due to the phase inductance, the stator phase current cannot be established instantaneously, thus torque ripple is inevitable at every phase commutation. Sinusoidal BLDC motor can also operate in this way, but the torque ripple will be in sinusoidal shape due to the sinusoidal back EMF and phase commutation.

1.6 Thesis Organization

Chapter 1 gives the brief introduction about my work. It’s also review on the brushless dc (BLDC) motor drive along with the review on the control of BLDC motor. Motivation and objective with brief description of the work is presented.

Chapter 2 describes the working principle of BLDC motor. Operation of BLDC motor with inverter in different modes of operation. Rotor position sensor used in BLDC motor to sense the rotor position of the rotor. Also the dynamic model of the motor.

Chapter 3 describes the Voltage source inverter (VSI) and different PWM techniques used to control the VSI.

Chapter 4 describes the speed controller and the PI speed controller design for the BLDC motor.

Chapter 5 shows the simulation result of the VSI with different PWM techniques. Closed loop simulation of BLDC motor with commutation circuit and space-vector PWM inverter and conclusions and future work.

Chapter 2:

BRUSHLESS DIRECT CURRENT MOTOR

2.1. Brushless DC motor

A BLDC motor is a permanent magnet synchronous motor. Position sensors are used to sense the rotor position according to the rotor position inverter control the stator currents thus the speed of motor. The term dc comes in the name of BLDC because its torque speed characteristics are similar to that of dc motors. BLDC requires an electronic commutation circuit instead of mechanical or brushed commutation used in dc motor.

BLDC motor are divided into mainly two types based on the shape of back-emf waveform induced in the stator are sinusoidal type and trapezoidal type. Sinusoidal motor have a sinusoidal shaped back-emf and its require phase current to be sinusoidal for torque ripple free operation on the other hand trapezoidal motors need rectangular shaped current for torque ripple free operation.

The trapezoidal motor requires position sensors to sense the position of rotor at every instant of time. It's requires a complex hardware for smooth operation. The trapezoidal motor is more popular for most of the application due to its simple operation, low price and high efficiency.

Many different configurations of BLDC motor exists three phase motors with star connected windings are most popular in use today because of its high efficiency and lower torque ripple.

2.2. Principle of Operation of Brushless dc motor

The three phase BLDC motor is operated by energizes two phase at a time, i.e. the only two phase are energized at an instant of time while the third phase is off to produce the highest torque. The two phases which are energized determine by an electronic commutation circuit depends on the output of the sensors. Hall-effect sensors are most commonly used to sense the rotor position and feed it to the controller. The signal from the sensors changes every 60° (electrical degree) as shown in figure.. Each interval starts with the rotor and stator flux is 120° apart and ends when they are 60° apart. Highest torque is reached when the field are perpendicular to each other. Commutation is done by a Voltage source inverter. The switching devices used are MOSFET or IGBT.

2.3. Operation of BLDC motor with Inverter

A trapezoidal PM machine gives performance closer to a dc motor. For this its known as a brushless dc motor (BLDC). It is an electronic motor and requires a three-phase inverter to the driving side for feeding power into the machine, as shown in figure 3. The machine is represented by its equivalent circuit, which consists of stator resistanceR_s, self-inductance L_s, and a back-emf. The inverter works as an electronic commutation which performs the switching according to the output from the position sensors. The inverter operates in the following two modes [5]:

1) $2\pi/3$ angle switch-on mode
2) Voltage and current control PWM mode

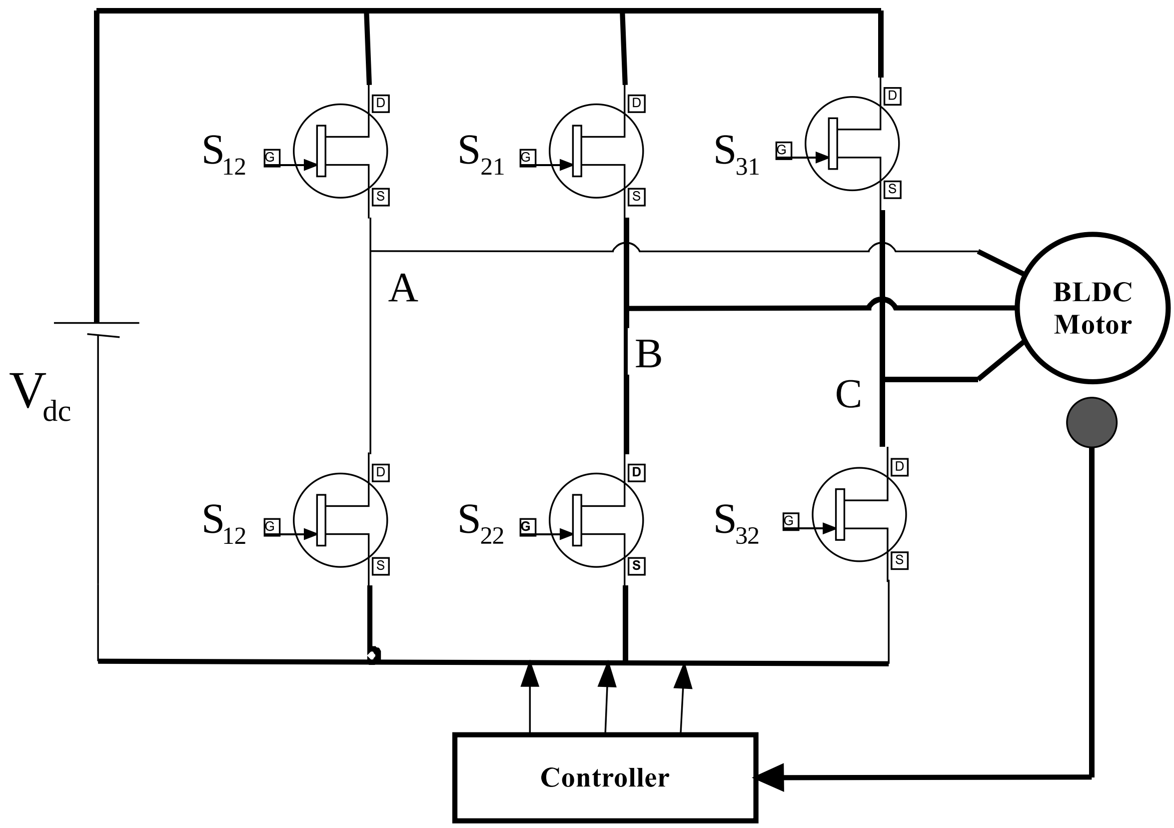


Figure 2. 1 BLDC Motor Drive [5]

2.3.1. $^{2\pi}/_{3}$ Angle switch-on mode

In this mode of operation all inverter switching devices (T_1 toT_6) are switch on-off in such a way that the current inputI_s is equally for the 2π / 3 angle at the centre of each induced back-emf voltage waveform. At an instant only two switches are on, one from the positive group and one from the negative group. For example, from instant t_1, T_1 and T_6 are conducting then the supply voltage V_s and input dc current I_s are applied across the AB phase of the inverter such that positive I_s will flow in phase A and negative I_s will flow in phase B. Then, after π / 3m interval T_6 is turn OFF and T_2 is turn ON, T_1 continues conduction for full 2π / 3 angle. The conduction pattern changes every π / 3 degree, with every switch has a conduction period of 2π / 3 degree. The switching sequence depends on the output of the position sensors [5].

2.3.2. Voltage and current control PWM mode

In the previous mode each switch of the inverter are switched ON-OFF for $2\pi / 3$ degree angle to generate the commutation function only. In addition to the commutation function. It is possible to controlled the voltages and currents continuously at the machine terminal by controlling the switches in PWM mode. There are essentially two modes for the current and voltage control operation of the inverter. These two modes are feedback (FB) mode and freewheeling mode. In both these modes switching devices are turned on and off for timing basis to controlled the machine current I_{av} and the machine average voltage V_{av} [5].

2.4. Rotor position sensors

For effective switching between phases we have to sense the rotor position effectively for sensing the rotor position Hall sensors are used. Hall sensors are placed in the stator casing of the motor 120° or 60° apart from one another.Whenever hall sensor comes in influence of rotor magnetic poles its produces a high or low signal according to the polarity of rotor pole. The signals from hall sensor are used to communicate with the electronic controller to rotate the motor in the right direction. For activating the hall-effect sensors magnetic field is required. Sensitivity of hall sensors depends on the placement of sensor's in the motor, air gap between rotor and sensor and magnetic strength of the permanent magnet rotor.

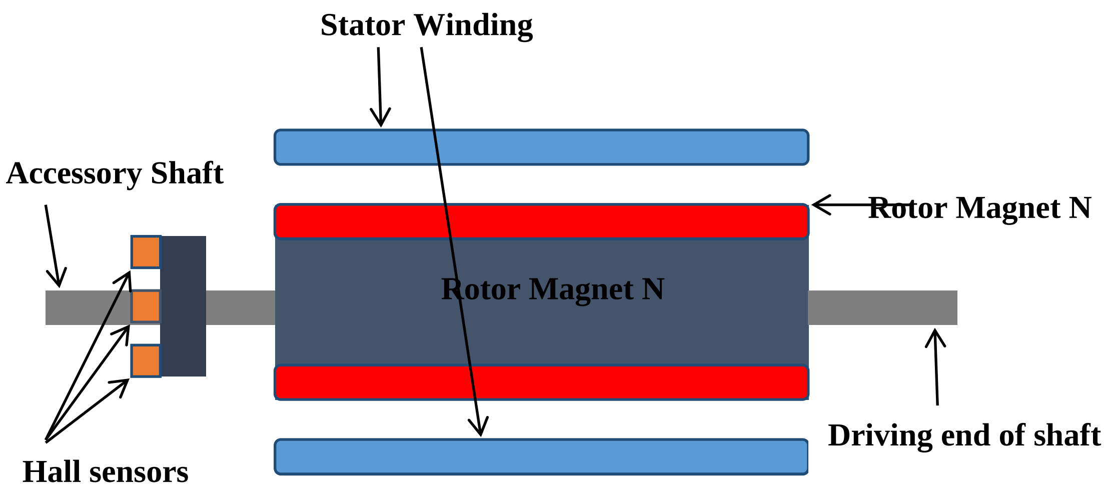


Figure 2. 2 Transverse view of BLDC showing hall Sensors [15]

2.5. Dynamic Model of BLDC Motor

The BLDC motor has three stator winding and a permanent magnet rotor [8]. Due to rotation of rotor emf is induced in the stator windings. Hence the circuit equations of the three windings are

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad 2.\ 1$$

Where we assume that stator resistance of all the windings are equal. The back-emf has trapezoidal shapes. Assuming that there is no change in the motor inductance with the rotation of motor[7], then

$$L_{aa} = L_{bb} = L_{cc} = L \quad 2.\ 2$$

$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M \quad 2.\ 3$$

Hence equation (1) becomes,

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad 2.\ 4$$

Where

$$v_{as} = v_{ao} - v_{no} \quad 2.\ 5$$

$$v_{bs} = v_{bo} - v_{no} \quad 2.6$$

$$v_{cs} = v_{co} - v_{no} \quad 2.7$$

For a balanced load the stator current is given by

$$i_a + i_b + i_c = 0 \quad 2.8$$

Therefore

Therefore in state space form the equations are arranged as follows:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad 2.9$$

The back-emf has trapezoidal shape and represented as

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \omega_m \lambda_m \begin{bmatrix} f_{as}(\theta_r) \\ f_{bs}(\theta_r) \\ f_{cs}(\theta_r) \end{bmatrix} \quad 2.10$$

Where, the angular speed of the rotor in radians per second, is the flux linkage, is the rotor position and the functions have same shape as. The induced emf is of trapezoidal nature.

The electromagnetic torque is defined as

$$T_e = \left[e_a i_a + e_b i_b + e_c i_c \right] / \omega_m (N-m) \quad 2.11$$

The moment of inertia is describe as

$$J = J_m + J_I \quad 2.12$$

The equation of motion is

$$J \frac{d\omega_m}{dt} + B\omega_m = (T_e - T_I) \quad 2.13$$

The relation between rotor speed and position is given by

$$\frac{d\theta_r}{dt} = \frac{p}{2} \omega_m \quad 2.14$$

The damping coefficient B is generally small and often neglected thus the system. The above equation is the rotor position and it repeats every 2π degree. The ground to neutral voltage is required to be considered in order to avoid inequality in the applied voltages. This is obtained by substituting equation (2.9) in the volt-ampere equation (2.5, 2 .6, 2.7) and adding then give as

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = R_s\left(i_a + i_b + i_c\right) + \left(L - M\right)\left(pi_a + pi_b + pi_c\right) + \left(e_a + e_b + e_c\right) \qquad 2.15$$

Substituting equation (2.6) in equation (2.14) we get

$$v_{ao} + v_{bo} + v_{co} - 3v_{no} = \left(e_a + e_b + e_c\right) \qquad 2.16$$

Thus

$$v_{no} = \left[\left(v_{ao} + v_{bo} + v_{co}\right) - \left(e_a + e_b + e_c\right)\right]/3 \qquad 2.17$$

Combining all the above equations, the state-space form of the system become

$$\dot{x} = Ax + Bu + Ce \qquad 2.18$$

Where

$$x = \begin{bmatrix} i_a & i_b & i_c & \omega_m & \theta_r \end{bmatrix}^t \qquad 2.19$$

I.e. the developed model is in term of variables and time as an independent variable.

$$A = \begin{bmatrix} -\dfrac{R_s}{L-M} & 0 & 0 & -\dfrac{\lambda_m}{J} f_{as}(\theta_r) & 0 \\ 0 & -\dfrac{R_s}{L-M} & 0 & -\dfrac{\lambda_m}{J} f_{bs}(\theta_r) & 0 \\ 0 & 0 & -\dfrac{R_s}{L-M} & -\dfrac{\lambda_m}{J} f_{cs}(\theta_r) & 0 \\ \dfrac{\lambda_m}{J} f_{as}(\theta_r) & \dfrac{\lambda_m}{J} f_{bs}(\theta_r) & \dfrac{\lambda_m}{J} f_{cs}(\theta_r) & -\dfrac{B}{J} & 0 \\ 0 & 0 & 0 & \dfrac{P}{2} & 0 \end{bmatrix} \qquad 2.20$$

$$B=\begin{bmatrix} \frac{1}{L-M} & 0 & 0 & 0 \\ 0 & \frac{1}{L-M} & 0 & 0 \\ 0 & 0 & \frac{1}{L-M} & 0 \\ 0 & 0 & 0 & \frac{1}{L-M} \end{bmatrix} \qquad 2.\,21$$

$$C=\begin{bmatrix} -\frac{1}{L-M} & 0 & 0 \\ 0 & -\frac{1}{L-M} & 0 \\ 0 & 0 & -\frac{1}{L-M} \end{bmatrix} \qquad 2.\,22$$

$$u=\begin{bmatrix} v_{as} & v_{bs} & v_{cs} & T_I \end{bmatrix}^t \qquad 2.\,23$$

$$e=\begin{bmatrix} e_a & e_b & e_c \end{bmatrix}^t \qquad 2.\,24$$

Chapter 3:

VSI and PWM Techniques

3.1 Six-Step VSI Inverter

BLDC motor drives are mostly used three-phase bridge inverters for supplying power to it. The circuit diagram of a six-step VSI is as shown in Figure 3.1, it comprises of three half-bridges, and these three are phase shifted by 120 degree to produce the three phase voltages. Figure 3.2 and 3.3shows the switching signal for upper and lower devices of the inverter.

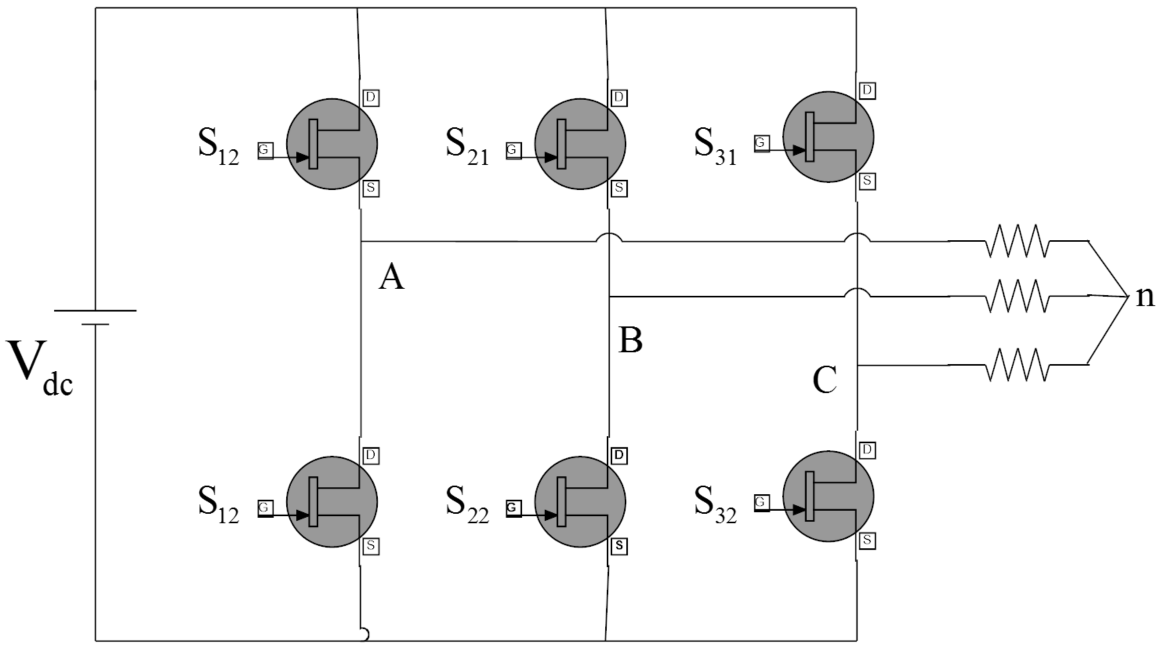


Figure 3. 1 Voltage Source Inverter

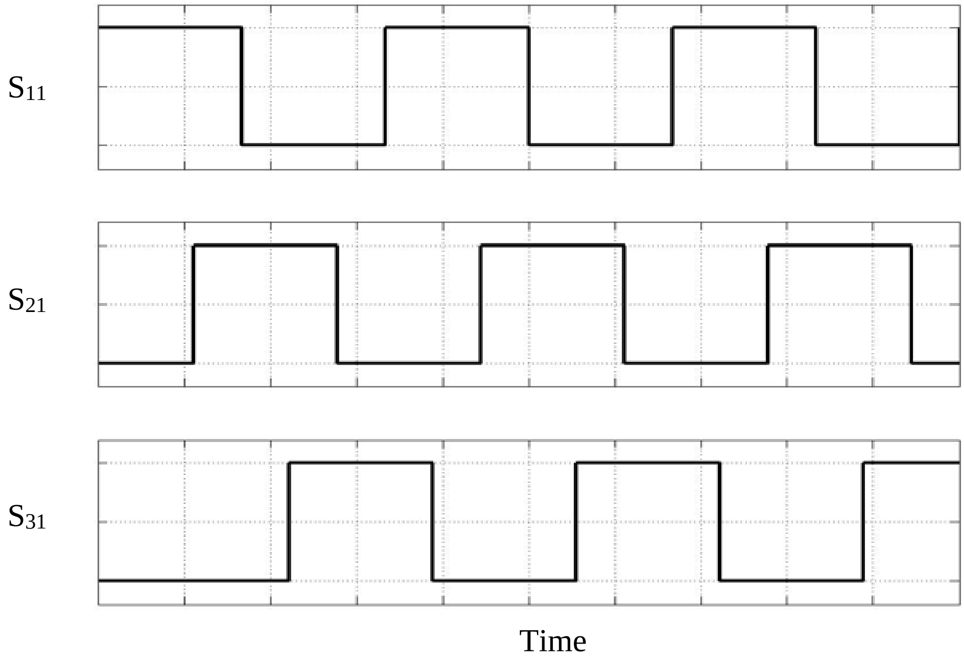


Figure 3. 2 Switching signals for the upper devices

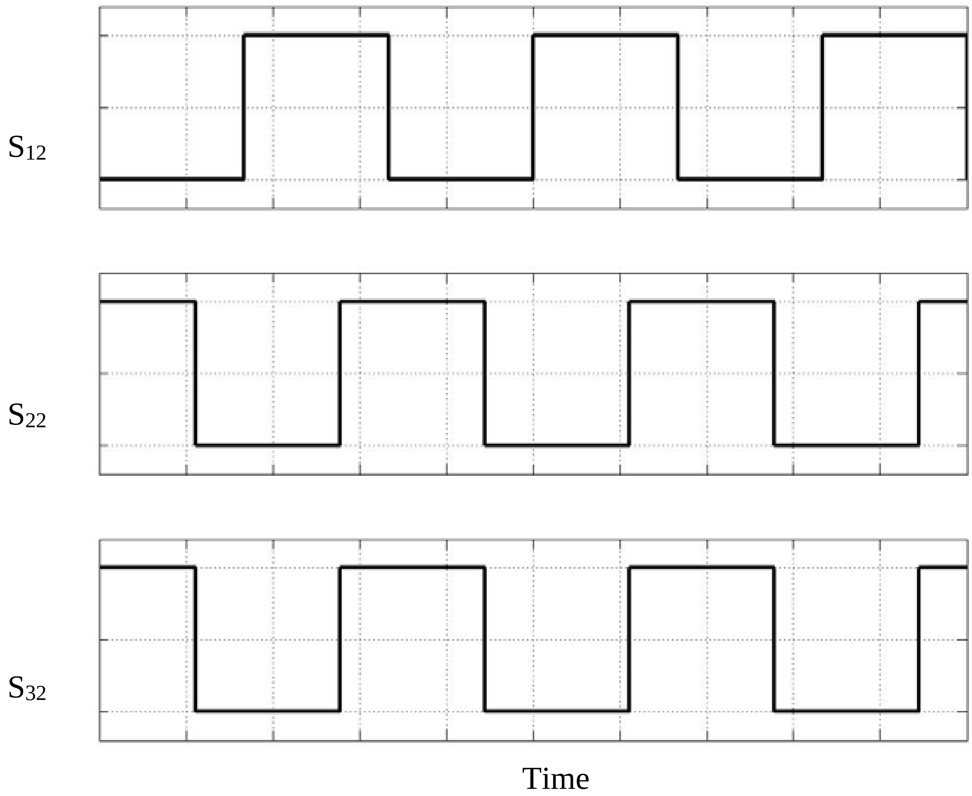


Figure 3. 3 Switching signal for lower devices

With the use of Fourier analysis the phase voltages with respect to the dc centre tap is expressed as,

$$V_{an} = \frac{2V_{dc}}{\pi}\left[\cos\omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t - \ldots\ldots\ldots\right] \tag{3. 1}$$

$$V_{bn} = \frac{2V_{dc}}{\pi}\left[\cos(\omega t - \frac{2\pi}{3}) - \frac{1}{3}\cos 3(\omega t - \frac{2\pi}{3}) + \frac{1}{5}\cos(\omega t - \frac{2\pi}{3}) - \ldots\ldots\ldots\right] \tag{3. 2}$$

$$V_{cn} = \frac{2V_{dc}}{\pi}\left[\cos(\omega t + \frac{2\pi}{3}) - \frac{1}{3}\cos 3(\omega t + \frac{2\pi}{3}) + \frac{1}{5}\cos(\omega t + \frac{2\pi}{3}) - \ldots\ldots\ldots\right] \tag{3. 3}$$

The line voltages can thus be obtained from the phase voltages as

$$V_{ab} = V_{an} - V_{bn} \tag{3. 4}$$

$$V_{ab} = \frac{2\sqrt{3}V_{dc}}{\pi}\left[\cos(\omega t + \frac{\pi}{6}) + 0 - \frac{1}{5}\cos 5(\omega t + \frac{\pi}{3}) - \frac{1}{7}\cos(\omega t + \frac{\pi}{6}) + \ldots\ldots\ldots\right] \tag{3. 5}$$

$$V_{bc} = V_{bn} - V_{cn} \tag{3. 6}$$

$$V_{bc} = \frac{2\sqrt{3}V_{dc}}{\pi}\left[\cos(\omega t - \frac{\pi}{2}) + 0 - \frac{1}{5}\cos 5(\omega t - \frac{\pi}{2}) - \frac{1}{7}\cos(\omega t - \frac{\pi}{2}) + \ldots\ldots\ldots\right] \tag{3. 7}$$

$$V_{ca} = V_{cn} - V_{an} \tag{3. 8}$$

$$V_{ca} = \frac{2\sqrt{3}V_{dc}}{\pi}\left[\cos(\omega t + \frac{5\pi}{6}) + 0 - \frac{1}{5}\cos 5(\omega t + \frac{5\pi}{3}) - \frac{1}{7}\cos(\omega t + \frac{5\pi}{6}) + \ldots\ldots\ldots\right] \tag{3. 9}$$

The fundamental value of the line voltages is √3 times to the phase voltage. The line voltage waveforms have a shape of six different steps thus the inverter is called six-step inverter.

3.2. PWM Techniques

Pulse-width modulation is a technique in which the ON-OFF time of switches is controlled by reference wave. In this the intersection between a reference wave and a carrier wave produces the pulses according to which the switches are switched ON and OFF.

PWM have a wide field of applications such as motor speed control, converters, communication, etc. For example PWM is used to control the switches of inverter to control the power supplied to the motor. By controlling the ON-OFF time of the switches we can control the speed of the motor. When we need more speed we increase the ON time of the switches similarly when we need to slow down the motor we decreases the OFF time of the switches. Higher switching frequency for the switches so that the power losses is insignificant as compare to the power supplied by the source.

There are different PWM techniques used for motor control application. We use the following techniques

1) Sinusoidal PWM
2) Space Vector PWM

3.3 Sinusoidal PWM

The sinusoidal pulse-width modulation (SPWM) technique is the most common and easy to generate pulses for the inverter. A high switching frequency results in a better output waveform. In this method the required output pulses are generated by controlling the frequency and amplitude of a modulating or reference signal. The variation in the frequency and amplitude of the modulating signal change the pulse-width of the switching pulses thus changes the output voltage.

The principle of SPWM is, a low frequency sinusoidal reference signal is compared with a very high-frequency carrier signal. The carrier signal has triangular shape. The switching pulses changes when the reference signal intersects with the triangular signal. The intersection positions determines the switching time. Frequency of output voltage depends on the frequency of the reference and switching frequency depends on carrier frequency.

In a SPWM, we compare the sinusoidal control signals (V_a, V_b and V_c), which are 120 degree apart with each other with a triangular voltage signal (V_T). Intersection of triangular signal with each phase of the sinusoidal control signal produces switching signal for each phase of the inverter.

An inverter has six switching devices S_{11} to S_{32} with output of each phase is connected to the centre of each inverter leg as shown in figure 3.1. There are two switch in each leg of the inverter and ON and OFF in a complementary fashion. That is, only one switch will conduct at any instant of time in one leg of inverter. The pole output voltage of the inverter varies between $V_{dc}/2$ to -$V_{dc}/2$ where V_{dc} be the total DC voltage.

For modulating index less than one peak of triangular carrier signal is always greater than the peak of sinusoidal control signal. When the carrier signal is less than the sinusoidal signal, the upper devices are conducting and the lower devices are OFF. Similarly, when the triangular signal is less than the sinusoidal signal, the upper devices is OFF and the lower devices are conducting. The switches in each leg of the inverter are controlled together and the control signal is:

S_{11} Is ON when $V_a > V_T$ S_{12} is ON when $V_a < V_T$

S_{21} Is ON when $V_b > V_T$ S_{22} is ON when $V_b < V_T$

S_{31} Is ON when $V_c > V_T$ S_{32} is ON when $V_c < V_T$.

V_a, V_b and V_c are the amplitude of reference and V_T is amplitude of carrier.

The inverter line-to-line is obtained from the pole voltages as:

$$V_{ab} = V_{ao} - V_{bo} \quad 3.10$$

$$V_{bc} = V_{bo} - V_{co} \quad 3.11$$

$$V_{ca} = V_{co} - V_{ao}. \qquad 3.12$$

3.4. Space Vector PWM

The Space Vector PWM (SVPWM) is the most widely used inverter switching mechanism for three-phase inverter used for BLDC motors. It achieves the voltage vector control by adjusting the timing and duty ratio of the eight switching states of the three-phase inverter. Assuming that stator coils in the three phases are identical, each switching state of the three-phase inverter corresponds to a voltage vector in the three-phase stator coil frame. Therefore

corresponds to eight switching state there are eight voltage vector (v_0 to v_7) as shown in figure 3.3, and their corresponding switch states are shown in table 3.1 [13]. v_0 and v_7 are zero vectors having zero magnitude v_1 to v_6 are six active vectors with fixed magnitude and 60° apart from each other. For example for switching state (0, 0, 1) for the phase (a, b, c) of the three-phase inverter. The lower gates of phase A and B are turn ON and upper gate of phase c is turn ON.

For any reference voltage vector which falls in the three-phase frame, we can resolve this vector using the combination of the eight voltage vectors. For example, the reference Vector shown in Figure 3.5 can be resolved by using two adjacent vectors v_1 , v_2 and the zero vectors v_0 , v_7 as

$$\mathrm{v} = \mathrm{d}_1\mathrm{v}_1 + \mathrm{d}_2\mathrm{v}_2 + \frac{1}{2}\mathrm{d}_3\mathrm{v}_0 + \frac{1}{2}\mathrm{d}_3\mathrm{v}_7 \qquad 3.13$$

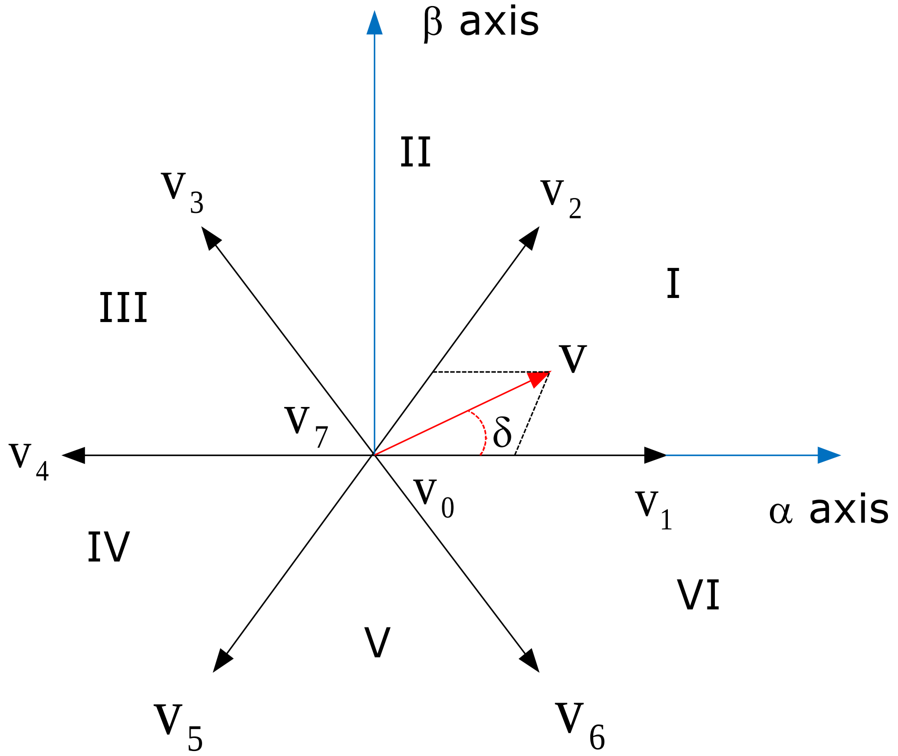


Figure 3. 4 Eight switching vectors

Voltage Vectors	Switching state			Phase Voltage($\times V_{dc}$)			Line voltage($\times V_{dc}$)		
	a	b	c	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
v_0	0	0	0	0	0	0	0	0	0
v_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
v_2	1	1	0	1/3	1/3	-2/3	0	1	-1
v_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
v_4	0	1	1	-2/3	1/3	1/3	-1	0	1
v_5	0	0	1	-1/3	-1/3	2/3	0	-1	1
v_6	1	0	1	1/3	-2/3	1/3	1	-1	0
v_7	1	1	1	0	0	0	0	0	0

Table 3.1 Eight active vectors according to the switching states

Where d_1 and d_2 is the duration for which vector v_1 and v_2 is applied respectively and d_3 is the duration for which zero vectors (v_0 and v_7) are applied. Any voltage vector located in the six sectors can be expressed as

$$\vec{v} = d_1\vec{v}_k + d_2\vec{v}_{k+1} + \frac{1}{2}d_3\vec{v}_0 + \frac{1}{2}d_3\vec{v}_7 , \qquad 3.\ 14$$

where

$$d_1 = \frac{\vec{v}}{\vec{v}_k}\frac{\sin\left[\pi/3-\left(\delta-k\pi/3\right)\right]}{\sin\left(\pi/3\right)} \qquad 3.\ 15$$

$$d_2 = \frac{\vec{v}}{\vec{v}_{k+1}}\frac{\sin\left(\delta-k\pi/3\right)}{\sin\left(\pi/3\right)} \qquad 3.\ 16$$

k = 1, 2… 6 is the sector corresponds to figure 3.5 the on/off time for switches is calculated as

$$T_a = d_1T_s$$

$$T_b = d_2T_s$$

$$T_0 = d_3T_s$$

Where T_s is the time period of the carrier signal. That is $T_s = 1/f_s$, f_s is the frequency of the PWM signal. T_a , T_b and T_0 are the time period for which two active vector and zero vector has been applied. The switching time for each switch in each sector is shown in the table 3.2 [13].

Sector	Upper Devices(S_{11}, S_{21}, S_{31}); Lower Devices (S_{12}, S_{22},S_{32})
1	S_1= T_a+ T_b+ $T_0/2$, S_2= T_b+ $T_0/2$, S_3= $T_0/2$
2	S_1= T_a+ $T_0/2$, S_2= T_a+ T_b+ $T_0/2$, S_3= $T_0/2$
3	S_1= $T_0/2$, S_2= T_a+ T_b+ $T_0/2$, S_3= T_b+ $T_0/2$
4	S_1= $T_0/2$, S_2= T_a+ $T_0/2$, S_3= T_a+ T_b+ $T_0/2$
5	S_1= T_a+ $T_0/2$, S_2= $T_0/2$, S_3= T_a+ T_b+ $T_0/2$
6	S_1= T_a+ T_b+ $T_0/2$, S_2= $T_0/2$, S_3= T_a+ $T_0/2$

Table 3.2 Switches on-off timing in each sector

Chapter 4:

CONTROLLER DESIGN FOR BLDC MOTOR

4.1 Commutation Strategies

For driving the BLDC motor, we need an electronic commutation circuit. For this we use a position based commutation for producing maximum torque in the motor. There are many commutation methods are used for BLDC motor mainly are sinusoidal commutation, trapezoidal commutation and field oriented control. In this we use trapezoidal commutation. Each of these methods has their advantages and implemented in different ways.

For rotor position sensing hall-effect sensors are used because they are cheapest of all and provide a better accuracy these hall sensors are placed at 120 degree apart in the motor and changes its state with every 60 degree rotation of rotor.

In trapezoidal commutation only two switching devices are kept ON, one on the upper half and one from lower half. This is one of the most popular methods used today because it is very easy to implement. Its uses a predefine sequence according to the output of the hall sensors. It is very efficient strategy but due to the fact that only two phases are supplied at a time its counters a torque ripple during operations especially in low speed operations. Therefore it is very popular low cost application. Because of the torque ripple generated due to irregularity in the commutation strategy, it produces noise and vibration in the motor. A current controller must be used to reduce the torque ripples, and it’s also doesn’t react to the transient torque generated because of the current transfer from one phase to another during commutation. For generating high torque with trapezoidal commutation we must use 180 degree commutation but its produce very high torque ripple as compare to 120 degree commutation. For every 60 degree operation one phase is switched ON and other is switched OFF. The electronic commutation circuit decides which to phases has to be supplied for proper operation of the motor. According to the rotor position electronic commutation circuit decides to supply the stator so that the motor rotates in the same direction.

4.2 Speed controller structure

Electronic commutation circuit guarantee proper rotation of BLDC motor, but the speed of the motor depends on the amplitude of the voltage fed to the motor. PWM techniques are used to control the magnitude of voltage fed to the motor thus control the speed of the BLDC motor. A speed controller is required to control the required speed. Many speed controllers are available for this we use a PI control scheme. PI controller is the most commonly used controller for industrial use because it is easy to implement. The input to the controller is the error between reference speed and actual speed of the motor. Based on the error signal the PI controller produces a control signal for the PWM block which changes the ON-OFF time of the switching devices in the inverter thus control the voltage fed to the motor. Figure 4.2 shows a schematic diagram of speed controller

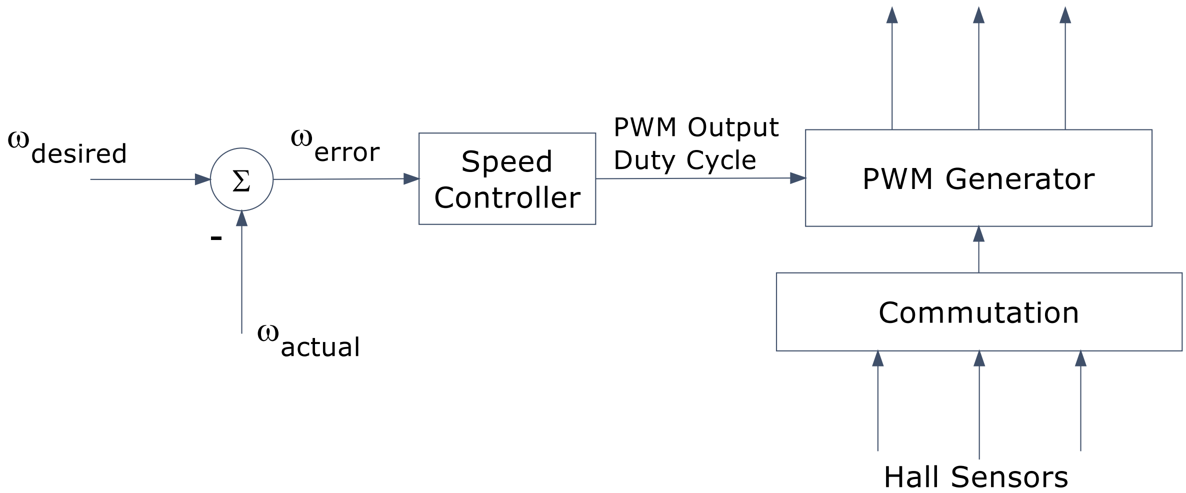


Figure 4. 1 Schematic Diagram of Speed Controller

The structure of speed controller is defined by the following equations:

$$u(t) = K_c \left[e(t) + \frac{1}{T_I} \int_0^t e(\tau)d\tau \right] \quad 4.1$$

Where,

$e(t)$ = Reference speed – Actual speed.

4.3 PI Controller Design for BLDC Motor Speed Control

The speed of the BLDC motor depends on the stator current value for controlling the speed of motor we have to control the stator current feed into the motor. We can control the value of stator current by controlling the average output voltage of the three-phase inverter which further depends on the on/off time of the six switches. Since the speed of BLDC motor is directly proportional to the inverter output voltage by varying the on/off time of the six switches.

The speed to voltage transfer function of BLDC motor is

$$G(s) = \frac{\omega_m}{V_s} = \frac{1/k_e}{\tau_m \tau_e s^2 + \tau_m s + 1} \tag{4. 2}$$

Where

ω_m = Speed of the motor.

V_s = applied voltage to the motor.

k_e = Back emf constant.

$\tau_m = \frac{3RJ}{k_e k_t}$ = Mechanical time constant.

$\tau_e = \frac{L}{3R}$ = Electrical time constant.

k_t =Torque constant.

L= Inductance per phase.

R= Resistance per phase.

J= Inertia of motor.

Based on the step response of the open loop bode plot, a PI controller is designed on the basis of the Ziegler-Nichols, Method.

Based on time response and experiences, Ziegler-Nichols proposed a tuning formula. The main objectives of the tuning of the PID controllers are as follows:

1. To minimize the rise time of the system.
2. Minimize the peak overshoot of the system.
3. Minimize the settling time of the system.

4.4 Ziegler-Nichols method for controller tuning

Based on the Step response of the system, Ziegler-Nichols proposed set of procedures to determine the proportional gain, integral gain and derivative gain.

Ziegler-Nichols method is used when the step response of the plant is an S-shaped curve

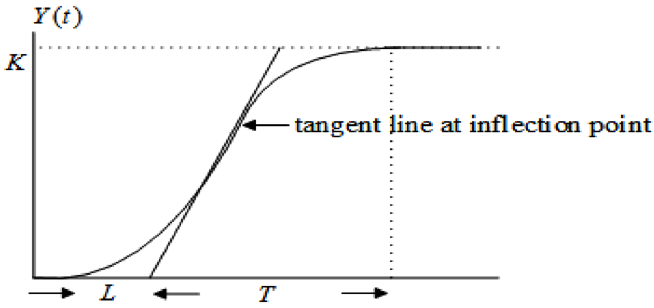


Figure 4. 2 S-shaped Curve

As shown in the figure 4.2. By drawing a tangent line at the point of reflection of the curve and determine the intersections point of the time axis and line Y (t) =K with the tangent drawn, as shown in figure 4.2 we can define the two characteristics of the curve that are time constant T and delay time L. Then the transfer function of the system may be approximated by first-order system with a transport lag as follows:

$$G(s) = \frac{Ke^{-Ls}}{Ts+1} \qquad 4.3$$

Ziegler and Nichols suggested setting the value of K_p, T_i will be:

$$K_p = \frac{T}{L} \tag{4. 4}$$

$$K_i = 0.9\frac{T}{L} \tag{4. 5}$$

Chapter 5:

RESULTS AND CONCLUSION

5.1 Simulation Result for PWM Technique.

5.1.1 Sinusodal PWM Technique

The simulation results of sine PWM twchnique is shown

$$V_{dc} = 300 \text{ V}$$

Inverter Frequency = 50 Hz

Switching Frequency = 5000 Hz

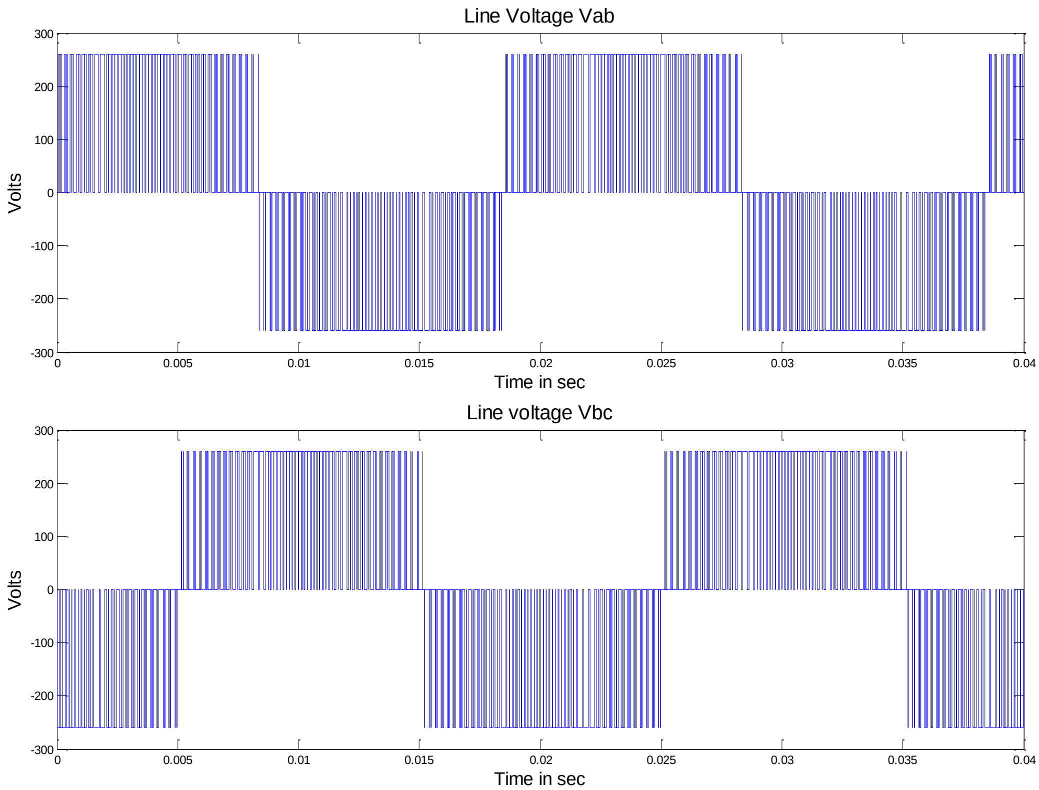
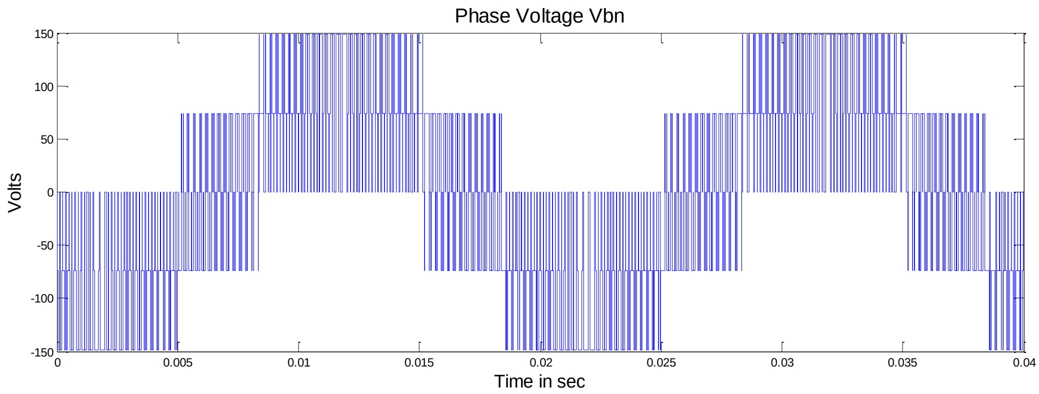


Figure 5.1 Line to Line Voltage output



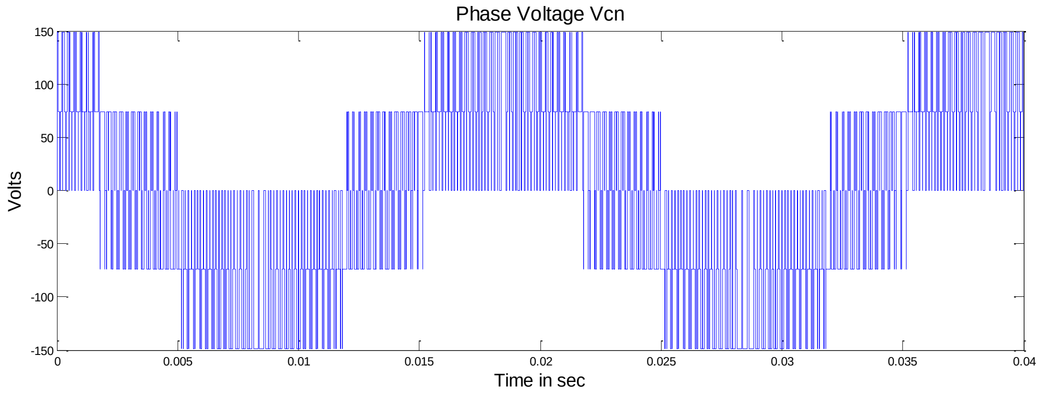


Figure 5.2 Phase voltage output

5.1.2 Space Vector PWM Technique.

The results of space vector PWM technique is shown below

Vdc = 300V

Inverter frequency = 50Hz

Switching Frequency = 4000 Hz

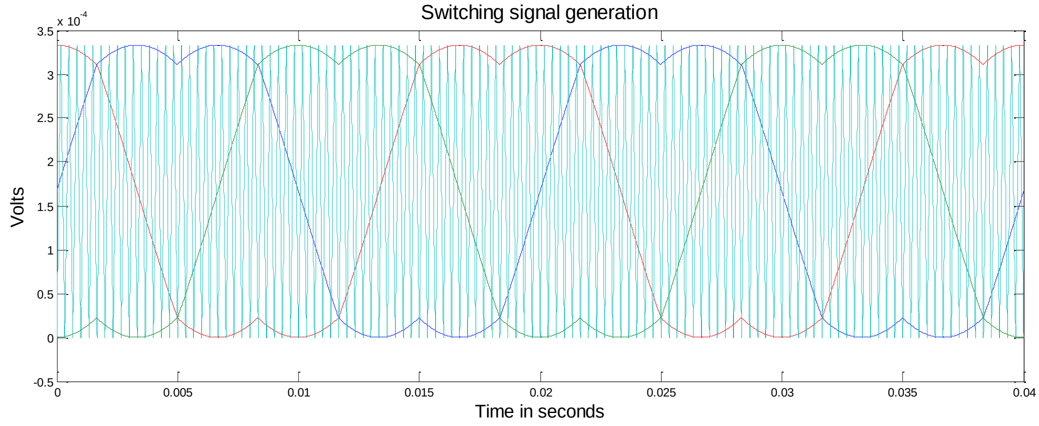
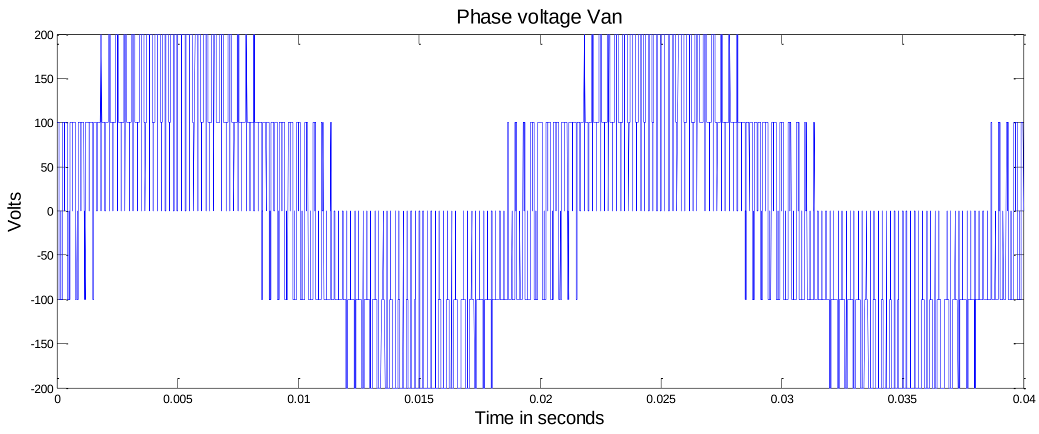


Figure 5.3 Comparison of time signals with triangular carrier signal



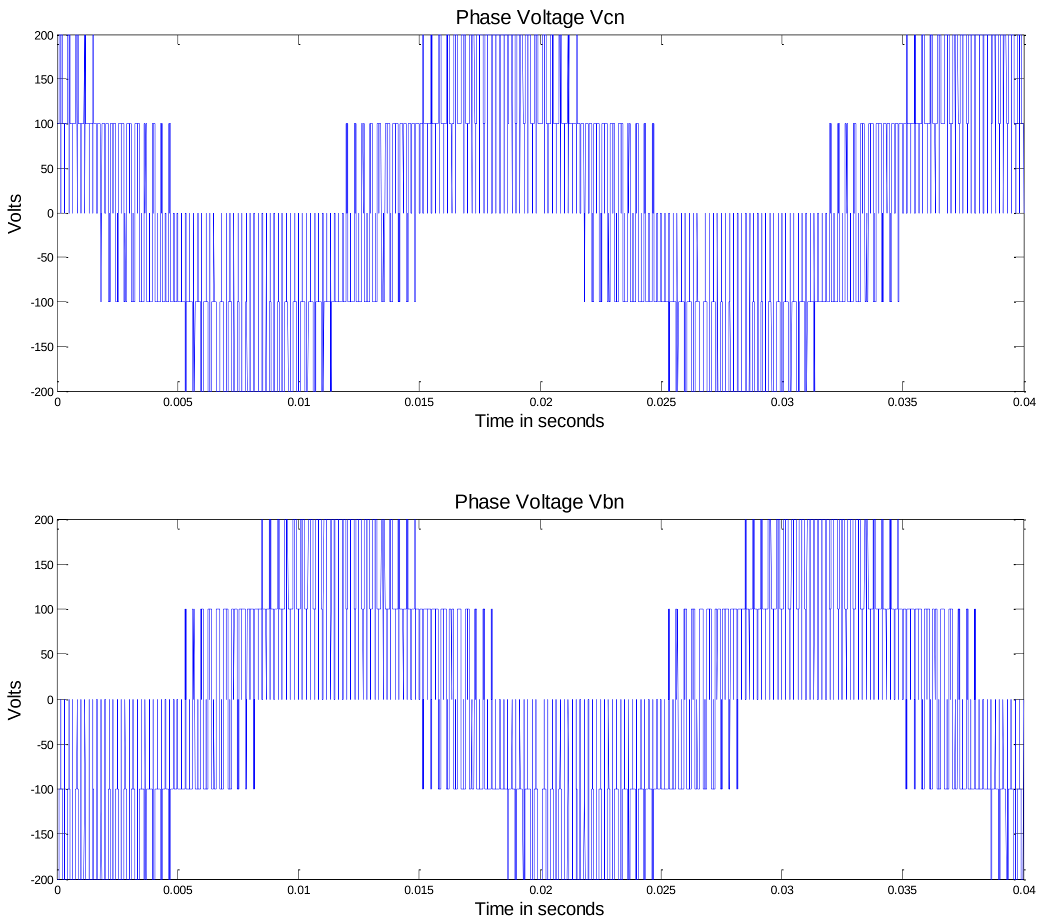
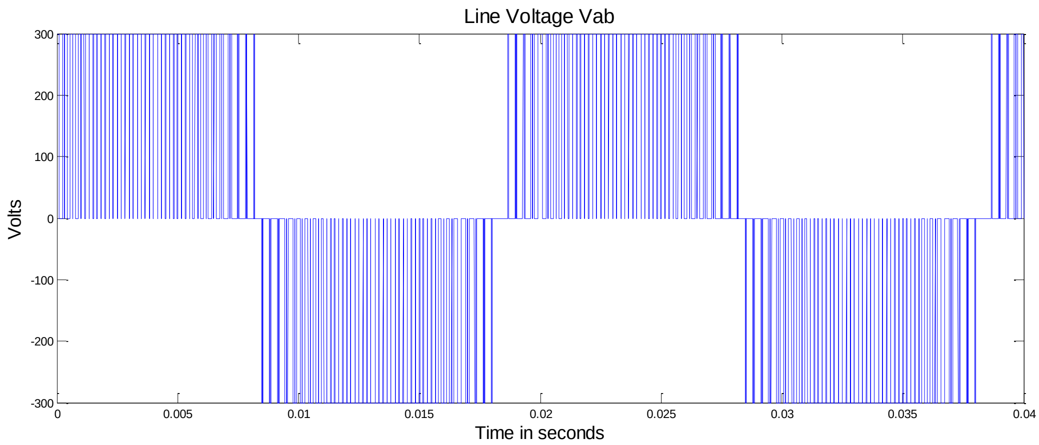


Figure 5.4 Phase to neutral voltage of Phase A, B and C



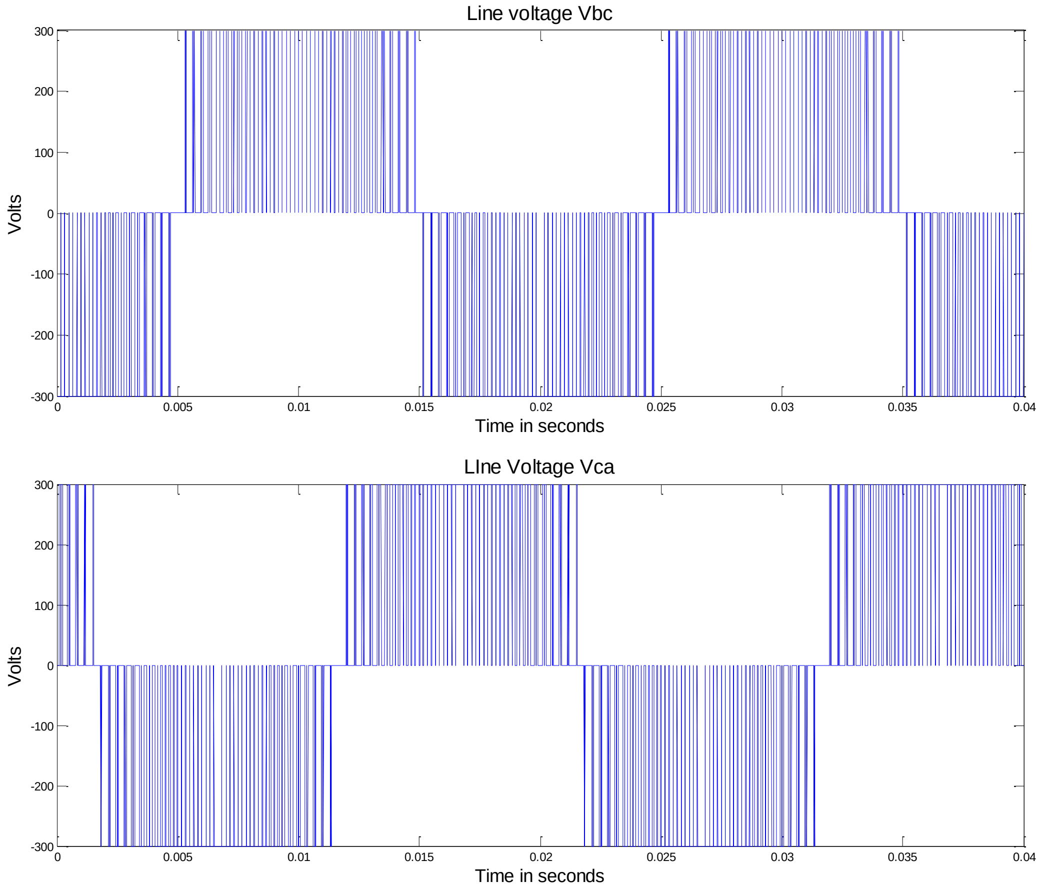


Figure 5.5 Line to Line voltages

5.3. Simulation Results with Commutation Sequence

In this inverter is work in $2\pi/3$ angle switched on mode. Each switch in the inverter is on for 120 degree. The output results are shown

Specification	Value
Resistance	2.875 Ω
Inductance	8.5 mH
Rotor Inertia	0.0008 Kgm^2
Friction Constant	0.001

Table 5.1 Motor Specification

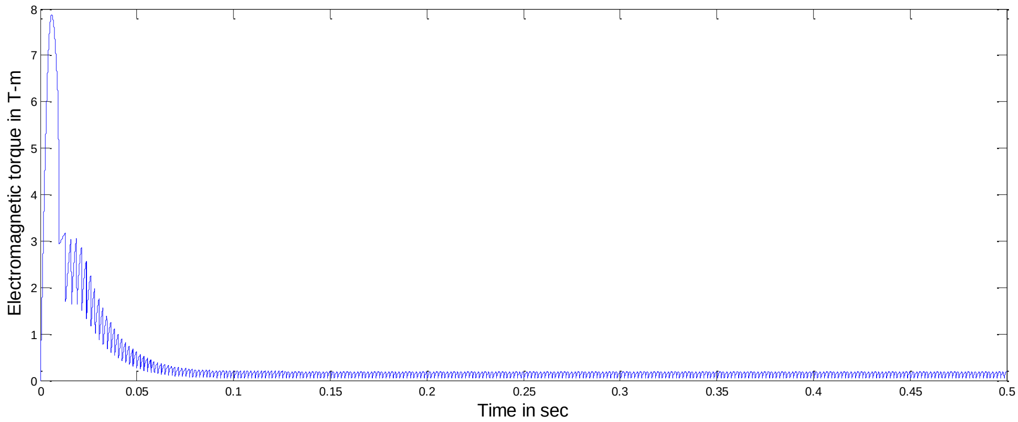


Figure 5.6 Electromagnetic torque developed in N-m

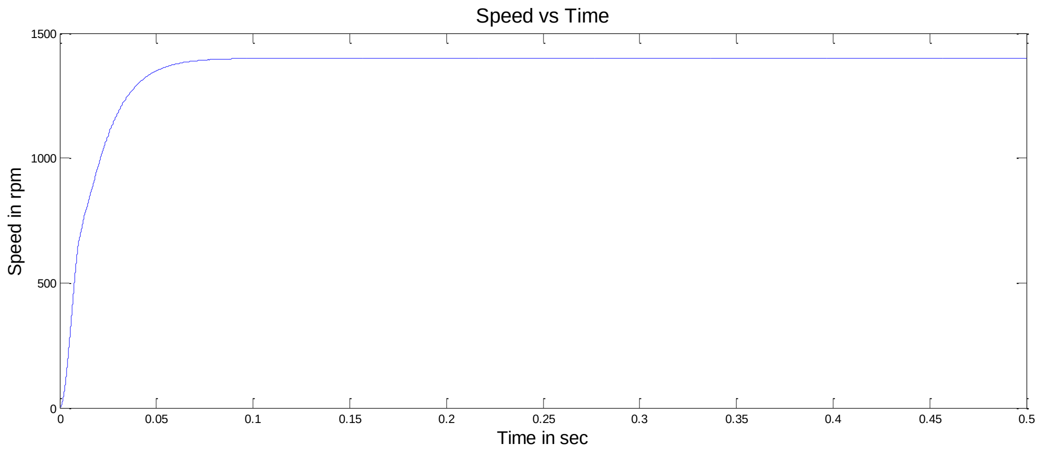


Figure 5.7speed response in rpm verse Time

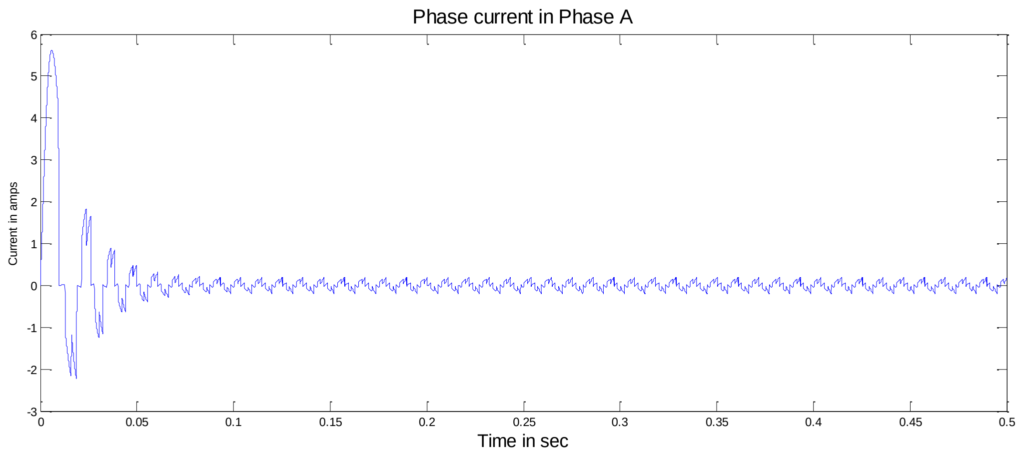


Figure 5. 8 Stator phase current of motor

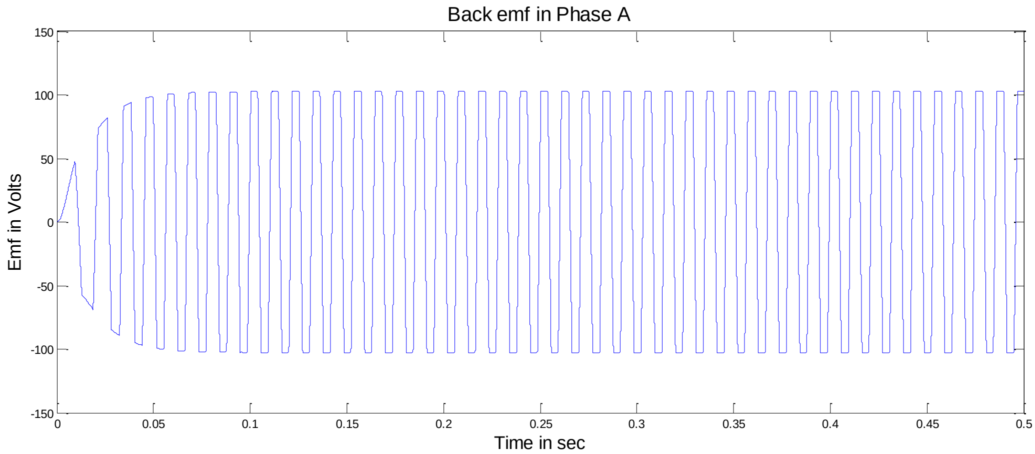


Figure 5. 9 Emf induced in the Stator

5.4. Simulation Results with SVPWM

SVPWM technique in used to control the duty ratio of switches of the three phase inverter. A PI controller is used to control the speed of BLDC motor drive. The value of proportional and integral gain is 0.015 and 12 respectively. The simulation results are shown.

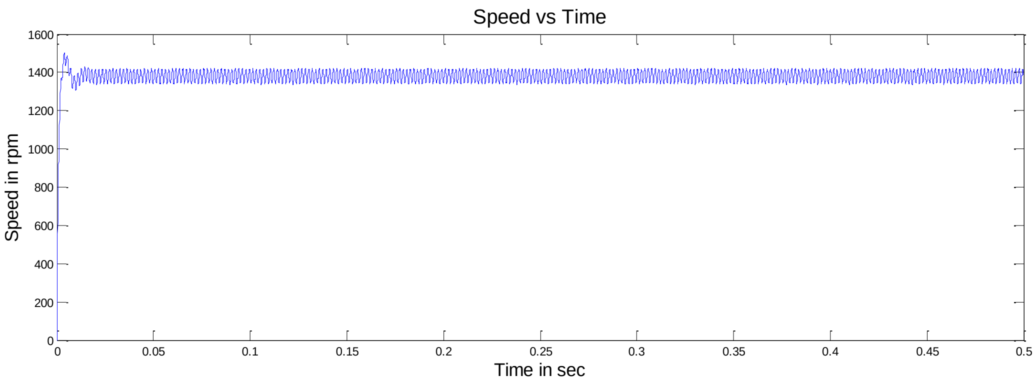


Figure 5.10speed response in rpm verses time

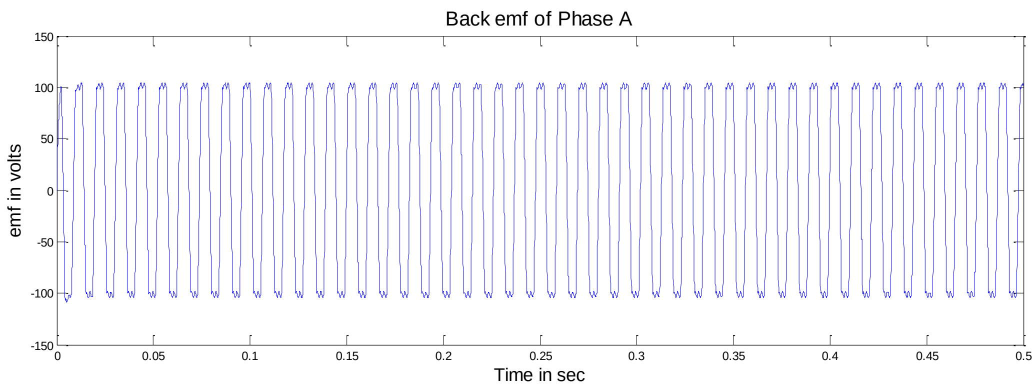


Figure 5.11 Emf induced in the stator

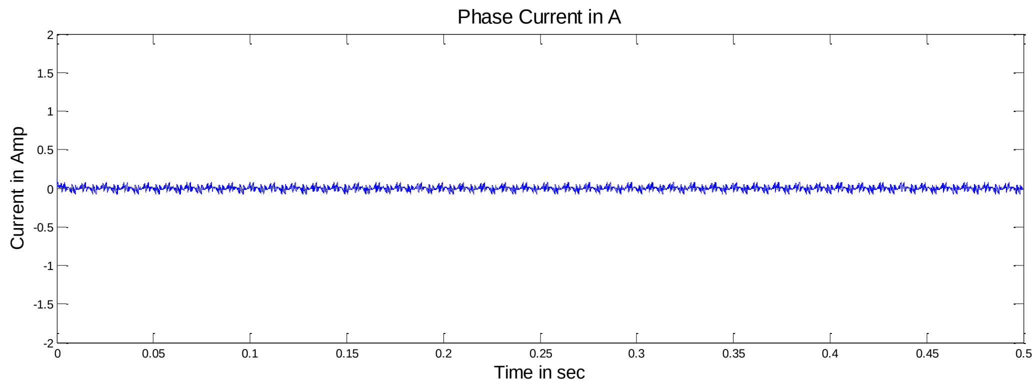


Figure 5. 12 Stator current of phase A

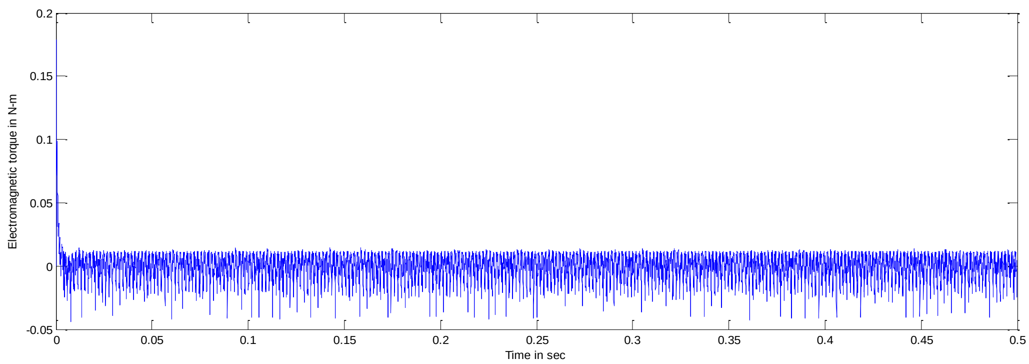


Figure 5. 13 Electromagnetic Torque developed in N-m

5.5 Conclusion

SVPWM provides a better result with the inverter as compared to the conventional SPWM technique for inverter. There is 15.5% increase in the line voltage of the inverter. SVPWM better utilized the available DC link power BLDC motor with SVPWM inverter and PI control scheme for speed control shows better results than 120 degree switch on mode. With SVPWM we achieve a better control over voltage and current supplied to the BLDC motor.

5.6 Future Work

Implementation of SVPWM using microcontroller. Implementation of other control algorithm for motor control. Hardware implementation of speed control of BLDC motor.

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